Future Directions in Geobiology and Low-Temperature Geochemistry

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A Report based on presentations and discussion by participants of the Future Directions in Geobiology and Low-Temperature Geochemistry Workshop, 27-28 August 2010, hosted by the Carnegie Institution of Washington, Geophysical Laboratory, Washington, D.C.

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Washington, D.C.

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Preface

Humanity is a confronted with an enormous challenge, as succinctly stated by the late Steven Schneider (2001; quoted by Jantzen, 2004), "Humans are forcing the Earth's environmental systems to change at a rate that is more advanced than their knowledge of the consequences." Geobiologists and low temperature geochemists characterize material from the lithosphere, hydrosphere, atmosphere, and biosphere to understand processes operating within and between these components of the Earth system from the atomic to planetary scales. For this reason, the interwoven disciplines of geobiology and low temperature geochemistry are central to understanding and ultimately predicting the behavior of these life-sustaining systems.

We present here recommendations from the workshop entitled "Future Directions in Geobiology and Low-Temperature Geochemistry." The report is a synthesis of written recommendations by many scientists and the concerted efforts of the workshop participants. We are deeply indebted to all of these individuals, as well as to S. Anderson, S. Brantley, M. Hochella, L. Kump, T. Lyons, J. Macalady and D. Newman for their reviews of the document. We are grateful to receive such thoughtful suggestions, comments and insights.

In this report, the geobiology and low-temperature geochemistry community offers recommendations that aim to leverage the intellectual and analytical capabilities of our scientific community to characterize Earth's past, present and future geochemical habitat as we enter the second decade of what E.O Wilson dubbed the "century of the environment."

Summary of Emerging Major Opportunities in Research and Education

- The rapidly expanding human need for land, energy and resources is transforming the geobiological and geochemical systems that are the foundation of our planetary habitat- the Critical Zone. Basic research into the operation of these systems has been and will increasingly be a foundation of our ability to sustain human well-being

- Major advances in analytical, molecular biological and computational tools provide the ability to understand fundamental biosphere-geosphere interactions at scales from the atom to the planet. Along with genomic data, the stage is set to explore the global consequences of these interactions.

- Understanding past biosphere-geosphere behavior is a powerful approach to understanding how our planet evolved, as well as anticipating how life-chemistry relationships will be impacted by human activity.

- Researchers working in teams and across disciplines can advance predictive tools to project, or "Earth Cast" geobiological and geochemical impacts of environmental change.

- Communicating scientific understanding of the Critical Zone and the services it provides to society will foster better-informed decision makers, an engaged citizenry and the next generation of scholars representing diverse racial, ethnic and gender backgrounds.

- We call for a bold initiative in <u>observatory science</u> that strategically augments current efforts and establishes new observatories for characterizing the evolving state of the Critical Zone, fueled by fundamental advances resulting from <u>basic research</u> in geobiology and low-temperature geochemistry.

I. Characterizing Earth System Geochemistry and Geobiology

The geochemical/biogeochemical consequences of human planetary alteration are truly profound. Only the most extreme geobiological changes recorded in the geological record capture the magnitude of human perturbation of the Earth surface today. Yet, we can use these rapid ongoing modifications to probe the complex web of geochemical and geobiological processes and feedbacks that required millennia or longer to transpire over Earth's history. New tools and means to chart ancient life-geochemistry relationships allow us to understand habitability of our planet as well as others, while also providing powerful insight to the biogeochemical transformations resulting from human activity.

A. Understanding Modern Planetary Change: The Anthropocene

Humans are managing and altering 50% of the Earth's land surface and transforming the physical, chemical and biological states and feedbacks among components of the Earth surface system. The surface system was named the "Critical Zone" in the 2002 NRC Basic Research Opportunities in the Earth Sciences (BROES) report. Human-induced changes are so profound that the onset of the industrial revolution is proposed to mark a new geologic era – the Anthropocene. In this short time, soil erosion rates have accelerated, metals and toxins have been mobilized far beyond natural rates, freshwater usage has grown to exceed recharge in major population centers, and ecosystems have been heavily impacted by fragmentation, extinction, global-scale biogeographic shifts and invasive species.

Figure 1. Some believe that the Anthropocene began about the time of the industrial revolution. Others would put it with the rise of agriculture.

Although impacts of land use may exceed climate impacts today, the potential release of greenhouse gases far exceeds the uptake capacity of the Earth surface. A shift to a new climate state is inevitable: one without polar ice, with more acidic oceans and with shifting meteoric water fluxes. We are increasingly aware of the need to move away from fossil energy and are striving to develop better ways to harness wind, solar, nuclear, and biological energy resources. This re-envisioning of our energy systems is exciting, but it comes with the responsibility to consider environmental footprints of each energy alternative at the scale needed to meet human demand for electricity, heat, transportation and industry.

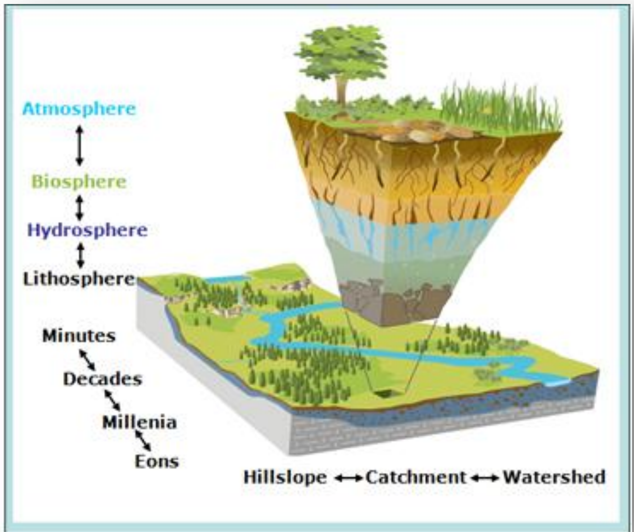


Figure 2. The critical zone is the heterogeneous near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources. (Image: J. Chorover)

Human land modification, climate change and energy use are transforming the geochemical and geobiological landscape. We are witnessing the wholesale reorganization of elements, chemical compounds, and water cycles on a global scale. This is yielding a global change in the distributions of organisms- a change that is increasingly recognized for macro-flora and fauna but remains virtually uncharted in the microbial realm. A **major research opportunity** is emerging to characterize the fundamental processes at work in the Critical Zone and use this knowledge to recognize how humans and human-induced perturbations are transforming the foundation of life's habitat.

B. *Leveraging the Deep Time Record to Understand* **Life and its Geochemical Habitat**

Interactions between organisms and their surroundings have played out over billions of years to define our planet's life-sustaining outer shell. These interactions continue today, shaping the Critical Zone in which we live. Our future depends on such interactions as they unfold over the coming centuries –and on our thoughtful and responsible stewardship of them. Yet, to understand our future, we need to know our geochemical and geobiological past.

Figure 3. Paleosols are an important archive of our ancient 'critical zone.' The charismatic red floodplain soils of the Willwood Formation, at Polecat Bench (near Powell, Wyoming) are part of an expanded terrestrial section of the Paleocene-Eocene Thermal Maximum (PETM) , an abrupt climate hyperthermal event (photo: K. Freeman).

The Earth's environmental systems have experienced geochemical, climatic and biotic change, with conditions in the distant past remarkably different from those of the Holocene epoch, when benign climatic conditions fostered human civilizations. Earth's history provides numerous analogues to the emerging climate state of dramatically warmer temperatures and highly elevated atmospheric CO_2 concentrations. But geologists have also documented that life's planetary habitat has undergone even more profound geochemical transformations. For example, the advent of biological oxygen production and the expansion of plants onto land are both changes that globally reorganized element fluxes and concentrations in the ocean, sediments and atmosphere.

Only the geologic, geochemical and paleontological records of Earth history can provide examples of change that rival the scale of the human-induced changes in land, biota, and climate that we are experiencing today. Thus, understanding past biosphere-geosphere behavior is a powerful approach to anticipating how life-chemistry relationships may be impacted by human activity in the coming decades. Earth's biogeochemical history provides a **major research opportunity** to investigate the geologic record to unlock its messages for the future of our planet.

Knowledge of geosphere-biosphere interactions is an essential complement to one of the most rapidly evolving fields of science: the search for, and exploration of, planets both within and outside our solar system. As Earth-like planets are discovered in the coming decades, we will only be able to assess their potential as abodes for life if we understand geosphere-biosphere interactions on a planetary scale, starting with Earth. Understanding the boundary conditions for life requires geobiological investigations in Earth's extreme environments, such as the deep subsurface and thermal springs. It is not an exaggeration that our understanding of geosphere-biosphere interactions will shape our perception of humanity's place in the Universe.

C. Powerful Insights Will Come from Integrating the Modern and Deep Time Approaches to Earth System Geochemistry and Geobiology

Geochemists and geobiologists recognize a grand challenge in modern Earth system science: to anticipate the future state of our planet. This "Earth Casting" of our habitat requires understanding of geochemical and geobiological mechanisms and their response to planetary drivers of change.

Figure 4. The red waters of the Rio Tinto are highly acidic and foster microbial biofilms that colonize the riverbed and are covered with yellow iron oxide precipitates. This geochemical system can preserve biomolecules and cell morphologies over thousands to millions of years and provides a modern example of an extreme geochemical habitat (photo: J. Macalady)

The response of an environmental system to human perturbation is inextricably linked to its own history. There is a **major research opportunity** to understand how biogeochemical legacies of past conditions or perturbations are manifest in sediment, soil, water, and associated faunal, floral, and microbial assemblages, and how they determine the resilience or vulnerability of that system to future perturbations. Because biogeochemical feedbacks operate over a range of timescales, understanding the consequences of human perturbation requires new scholarly partnerships between those who study modern processes and historically oriented geobiologists and geochemists. Modern and geological methods, data and models must be integrated in order to define and quantify linkages among environmental conditions and biological function and diversity.

Emerging Research Questions and Opportunities in Understanding Earth's Geobiological Systems:

- How have biosphere-geosphere interactions shaped the cycles of the elements and patterns of life through time?
- What are the climatic, biotic and chemical states that the Earth system has experienced through time, and how were they related and regulated?
- How will changing land use, emerging energy systems and growing resource demands impact elements and organisms within the Earth's geobiological and geochemical system?
- How do past processes and perturbations predispose an environment to be resilient or vulnerable to additional forcing?
- Will human activity push the Earth to a new geochemical state?
- What are the physical and chemical limits on where and how life can exist?

Figure 5. Mining complex, near Huelva, Spain. Massive Paleozoic sulfide deposits in the Rio Tinto reguion are enriched in metals such as copper, zinc, lead. Industrial age mining was preceded by mining activity by the Romans and there is geologic evidence for extreme acid rock drainage in the area as much as 1- 2 million years ago. (photo: J. Macalady)

II. A Revolution in Data and Knowledge

The Earth science community employs a rapidly expanding set of tools to observe, characterize, and predict fundamental Earth and life processes over temporal and spatial scales never before attained. These powerful analytical, genomic and computational advancements provide a ***major research opportunity*** *to advance understanding of biosphere-geosphere interactions at atomic, enzymatic and nanoscales, setting the stage to explore their global consequences.*

A. Data and Knowledge in Geochemical Systems

The natural world consists of a mixture of particles, gaseous and dissolved species, and organisms, with heterogeneous properties at all scales. We can now observe the distributions of elements, isotopes and their oxidation states, as well as crystalline and molecular structures at the finest scales in soils and sediments. Even though oxidized and reduced forms of the same element can be intermixed on micron scales, geochemical heterogeneity is not represented in measurements of bulk properties. This knowledge gap can be bridged with integration of observational scales, yielding both new metrics of heterogeneity and new understanding of its functional role in surface environments.

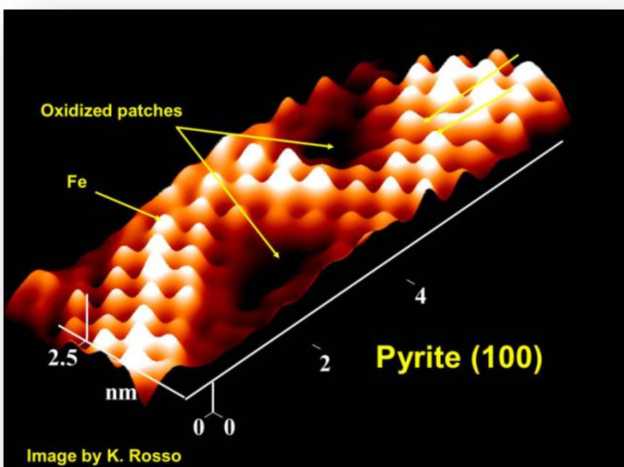


Figure 6. Scanning Tunneling Microscopy (STM) image of pyrite showing spatial patterns in oxidation. (Image: Mike Hochella and K. Rosso)

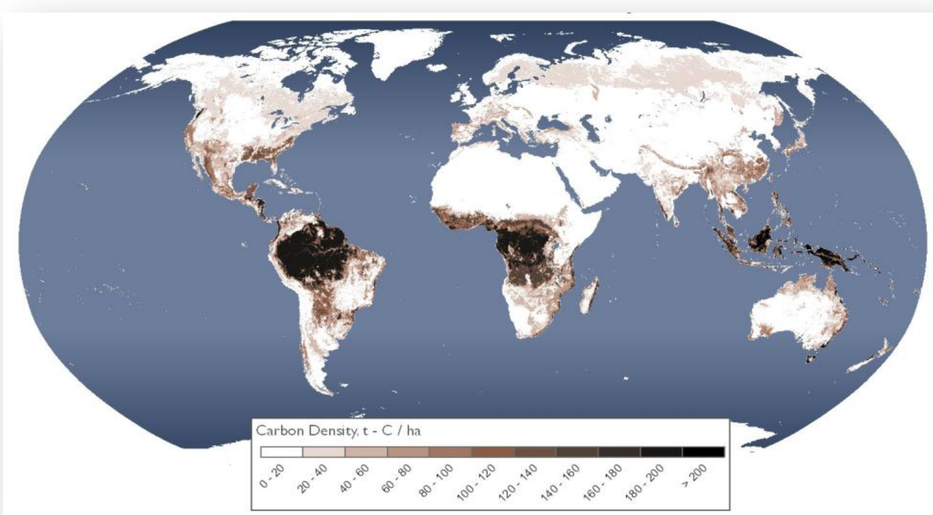
The importance of the nanoscale world is literally just coming into view, in part owing to the observational tools now available to our community. The chemical and physical properties of nanoscale minerals differ profoundly from their bulk-scale counterparts, and we understand almost nothing of how nanoparticles impact element cycling in the natural world. What we know of the cellular interactions between nanoparticles and microorganisms, plants, and fauna is equally scant. Filling in these knowledge gaps is of critical importance in light of the accelerating human production, application and disposal of nanomaterials. A great deal of work will be needed to characterize the role of nanoparticles in natural systems, and to anticipate the looming impacts of manufactured nanoparticles released by humans into the environment.

New advances in chromatography, spectroscopy and mass spectrometry provide an expanded analytical toolbox that enable molecular-level and mechanistic studies of metabolites, substrates, enzymes, co-factors and other sub-cellular agents that drive geobiological processes. Coupling new tools in molecular geobiology with the power of genomics, geochemical analytical techniques and theoretical models defines an immense new frontier in geobiology and low-temperature geochemistry.

Over the next decade, we will see the development of molecular-scale computational models with temporal resolution down to the nano- and pico-second timescales. Ultra-short, ultra-intense pulsed light and x-ray sources and time-resolved methods can be used to track the dynamics of transient reaction species and even generate ‘molecular movies’ of fast, fundamental processes. Advances in models for liquid- and solid-phase chemistry and rapid increases in computational power provide a potent opportunity for understanding complex geochemical systems.

Computational and analytical advances are enhancing one of the most powerful tools in the geochemical toolkit – isotopes. Software and computational power for molecular modeling can be used to predict the behavior of a wealth of isotope systems in geochemical and geobiological processes. New laser mass detectors are dramatically expanding observational light-mass isotopic data for water, CO_2, methane, and other gases. A new generation of mass analyzers continue to expand our knowledge of intermediate mass isotope systems, while enhanced methodologies for cosmogenic and uranium series isotopes allow researchers to date Critical Zone processes with increasingly finer detail.

Figure 7. Global map of biomass carbon (above and below ground). From: Ruesch and Gibbs (2008) IPCC Tier-1 Global Biomass Carbon Map for the Year 2000. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.



B. Data and Knowledge in Geobiological Systems

Modern DNA sequencing capabilities now allows us to characterize of the structures and processes of whole microbial communities. New advances allow the determination of tens of billions of bases per analysis and this scale of capacity is jump-starting the field of environmental genomics. Genomic data derived from environmental RNA reveals microbial dynamics on scales of minutes while data derived from DNA allows characterization of geobiological evolution over billions of years. The field is poised to address challenges facing humanity, including increasing soil fertility to aid in feeding the worlds growing population, providing novel approaches to Earth resources and waste disposal, and attenuating the impacts from human land use and climate change in the Critical Zone.

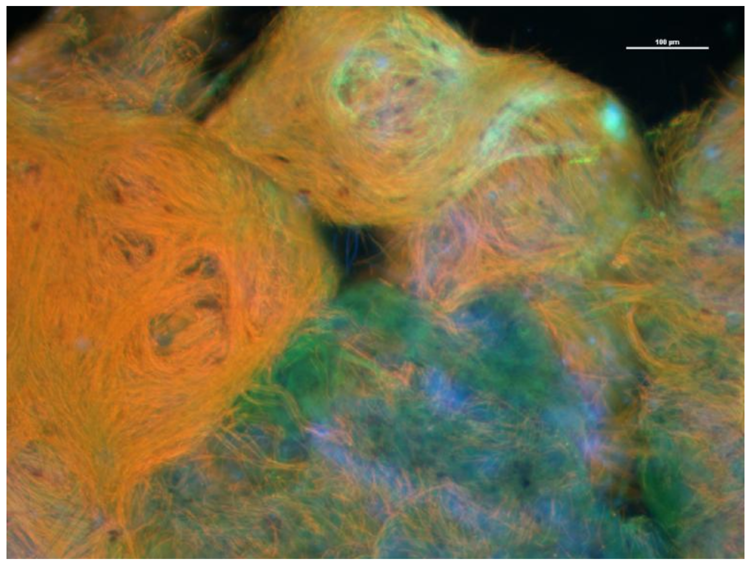


Figure 8. Filamentous organisms in a cyanobacteria-dominated mat growing in weakly sulfidic waters, Little Salt Spring, Florida. (Photo: J. Macalady)

The emerging revolution in DNA sequencing offers unprecedented insights into the elusive microbial communities that mediate Earth's elemental cycles and form the foundation for all life on the planet. With our growing ability to identify the biological diversity of microbes irrespective of whether they can be cultivated, we can now identify where these microbes are located in relation to each other and to Earth materials, and track their activity and geochemical roles over space and time. Never before has it been possible to obtain this information without having microbes in culture, and never before has so much data been collected. But this is just the tip of an immense "iceberg" of data that is beginning to appear, as the "meta-omics" world (meta-genomics, proteomics, transcriptomics) becomes visible.

The availability of inexpensive sequencing has moved studies of the interface between geochemistry and molecular biology to a new level. We can now collect nearly limitless amounts of molecular sequence data, allowing us to see the genetic complement of nearly any environment nearly instantaneously – vast quantities of base pairs can be "harvested" and analyzed to provide a DNA "snapshot" of the biodiversity and gene diversity of an environment, while monitoring of RNA and protein expression provides new avenues for probing geobiological dynamics in near real time.

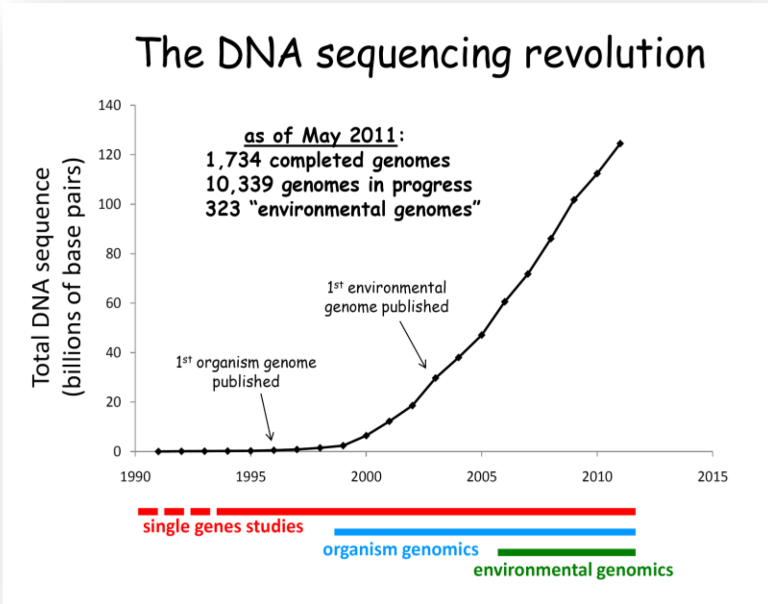


Figure 9. DNA sequences in public databases as of May, 2011. Advances in DNA sequencing technology have decreased costs and increased throughput, enabling rapid sequencing from single genes, to whole genomes (thousands of genes), to the genomes of communities of microorganisms (millions of genes). This provides methods for investigating the roles of microorganisms in geobiological processes (figure: G. Dick).

The explosion of DNA sequencing is unveiling staggering genetic diversity, but these new vistas are matched by a widening gap between gene sequence data and our understanding of its biochemical, ecological, and geochemical function. Much fundamental work is needed, including: 1) annotating and identifying new genes using classical and biochemical approaches; 2) sorting out the implications of genetic diversity within microbial taxonomic units; and, 3) filling the dearth of reference strains and genomes needed to test hypotheses generated via genomic and metagenomic approaches.

The sheer volume of data available at relatively low cost increasingly pushes analytical challenges into the realm of computer science, and is one of the major challenges of the next few years. Added to these computational challenges will be interfacing the omics data with geochemical/geological data – two data sets that are fundamentally different in terms of definition and quantification. Bringing the two fields together will ultimately allow each can to make predictions about the other: omics approaches open entirely new avenues for probing geochemistry, while the geochemical community can provide a rich context in which to understand molecular geomicrobiology. Integrating these communities has vast potential for transformative cross-disciplinary breakthroughs.

Emerging Research Questions and Opportunities Empowered by New Computational, Analytical and DNA-based Approaches:

- How do atomic and nanoscale properties influence macroscopic geochemical processes and global element cycles?
- How does geochemical and geobiological heterogeneity influence observed bulk properties and the rates, mechanisms and isotopic signatures of reactions?
- How do naturally occurring nanoparticles, as well as manufactured nanoparticles inadvertently entering the environment, affect life on Earth.
- What regulates cellular and sub-cellular agents in complex environmental systems?
- How does biodiversity relate to ecosystem function, stability, and resilience?
- What can the genetic record tell us about the history of life and its planetary habitat?
- How can we integrate genomics and the geologic record to probe the emergence of metabolic processes and their impacts on the geochemical states of the Earth?

Figure 10. The geochemistry and geomicrobiology of Bahamian blue holes is the focus study by international researchers. (Photo Janet Franklin).

III. Geobiology and Geochemistry in the Service of Society

A. Earth Casting

Cross-fertilization of ideas within the community of Earth scientists must occur to advance knowledge of our past and present to learn how to project our future. Assembling teams of scientists to systematically address this challenge through 'observatories' will amass the tools and perspectives needed for Earth casting. A **major research opportunity** exists to bring together researchers in teams focused on developing insights that cross disciplinary boundaries, and that culminate in providing predictive tools to project the geobiological and geochemical impacts of environmental change. Integrated science requires integrated data. We need to capture and make interoperable a much wider array of Earth science information and knowledge and allow its ready access to interdisciplinary teams.

B. Learning and Teaching Critical Zone Stewardship

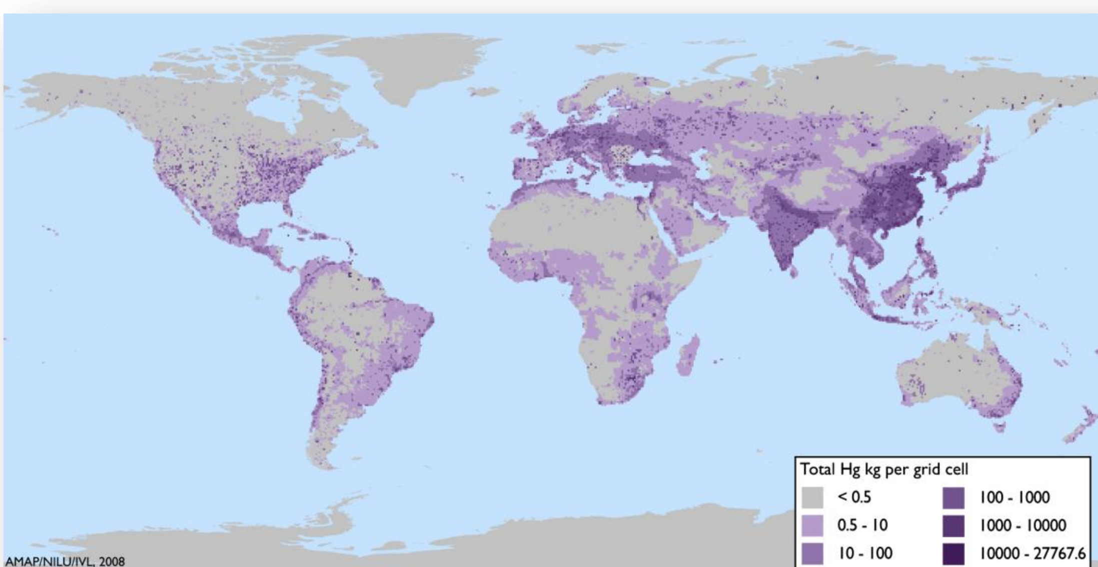
Geobiological and geochemical systems provide essential services to planetary ecosystems and the human societies nested within them. These services emerge from the geobiological and geochemical interactions that foster the availability of food, clean water, materials needed for shelter and industry, energy resources and waste disposal. Social stability and conflict, economic health, issues of environmental justice, and national security are all closely tied to such natural services and the human livelihoods that depend on them. The social and environmental impacts of human activities involved in resource acquisition, distribution, and disposal are profound. We need only read news report of oils spills, mining and industrial waste and environmental change to understand the importance of wise policy regarding Critical Zone services. Good stewardship relies on scientific understanding of highly complex systems, coupled with capable communication with decision makers and citizens.

There is a **major educational responsibility** to communicate understanding of Critical Zone services to a broad citizenry and to train the next generation of scholars representing all fields of physical, biological, and social sciences. By integrating disciplines, crossing spatial and temporal scales, and employing powerful observational and computational methods, today's geobiologists and low-temperature geochemists can provide insights that will help shape the future of human existence. Through outreach and education, we can empower current leaders and train future scientists with the knowledge needed to sustain healthy ecosystems well into the future.

Emerging Research Opportunities for Geobiology and Geochemistry in the Service of Society:

- How can we assemble the tools, data and diverse perspectives needed to understand geobiological and geochemical systems now being perturbed by changing land use, hydrology and climate?
- How can we understand geobiological and geochemical systems in human environments, including urban, rural, industrial, and managed landscapes?
- How can we use the geologic records, modern observations and computational tools to project the future of Earth's near-surface environment, the Critical Zone?
- How can we develop metrics of environmental resilience, vulnerability and services based on our knowledge of geobiological and geochemical processes?
- What are the most effective methods to communicate Critical Zone science to decision-makers and the public? How do we train scientists to do this?
- What are the best ways to teach about the Life-Earth interface from a systems perspective in ways that are meaningful to diverse ethnic and gender communities?
- How can we develop outreach programs that communicate the services of geobiological and low-temperature geochemical systems to diverse populations?

Figure 11. Global distribution of total mercury emissions (in 2005; kg Hg per 0.5^{o} grid cell) AMAP/UNEP, 2008, Technical Background Report to the Global Atmospheric Mercury Assessment.



IV. An Action Plan: Leveraging the Power of Observatory Science

Earth's environmental systems are under increasing stress and the consequences for plant, animal, and human populations may be calamitous. We must anticipate these impacts and we must pursue the science needed by policy makers to enable informed decisions that mitigate the consequences for society. Earth system science observatories can propel us across interdisciplinary divides and help us reach understanding of our planet's past and present Critical Zone. We propose enhanced Earth System Observatories that will create the capability to Earth Cast the future.

A. Linking Critical Zone and other Natural Observatories

An existing and planned suite of observatories provide powerful, yet not fully comprehensive insights into the operation of Earth's ecosystems. These include the sites within the NSF Critical Zone Observatory (CZO) and Long Term Ecological Research (LTER) programs, those identified within the Critical Zone Exploration Network (CZEN), and those proposed through the National Ecological Observatory Network (NEON). Each could be upgraded to address a wider range of variables and they can be collectively integrated to build a more comprehensive framework. *Specifically, NSF should move the Critical Zone Observatories toward a more productive program in the following ways:*

i) Add observatories to explore environmental variables such as anthropogenic impact, lithology, and time (including deep time)

ii) Target funding for science that links data emerging from CZOs, fostering cross-site science, and from observatories supported by other NSF directorates or agencies;

iii) Target fundamental experimental, field and computational science to address questions emerging from the observatories;

iv) Select new sites in ways that foster network priorities and recognize site priorities.

We call for an innovative approach to natural observatories that builds on the initial success of the CZOs, and strategically links current and new sites in order to foster integrated understanding of the surface environment and ecosystems of Earth.

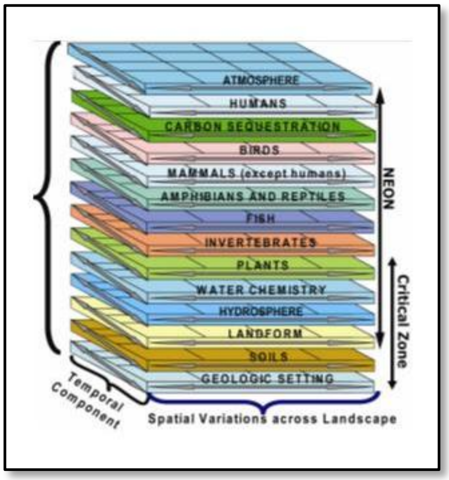


Figure 12; the comprehensive Earth environmental systems observatory concept (figure: N. Euliss, T. Winter, M. Goldhaber).

B. Comprehensive Earth Environmental Systems Observatories

Upgrading the existing networks of natural observatories and supporting basic research will help address the full spectrum of geologic, geochemical, biotic, climatic, and land use complexities. Yet, given the scale and scope of the anthropogenic changes to our planet, truly comprehensive observatory configuration is called for; one that systematically deploys the entire spectrum of Earth system science expertise.

i) Controlled Ecosystem Observatories

Experimentation that controls key environmental variables is an approach that is fundamental to natural science. A set of observatories allowing the manipulation of major climatic, material, hydrologic and ecologic variables should be implemented to identify the factors that endow Earth's surface environment with resiliency or vulnerability. These controlled settings can provide insights into the operation of surface processes that are exceedingly difficult to obtain in another fashion.

ii) Observatories that Bridge Spatial Scales

Geochemists now possess incredibly powerful tools that permit the characterization of fundamental processes at scales from submicroscopic to planetary. A a key link in this sequence of spatial scales is that between submicroscopic and microscopic processes on one hand, and macroscopic environments on the other. The focusing of fine-scale computational and observational approaches on systems (observatories) with high quality macroscopic environmental information will foster the scientific collaboration necessary to rapidly advance scale-dependent understanding of natural processes.

iii) Observatories that Bridge Time Scales

We propose a major role for observatories that bridge understanding of the geological record of past global 'states' with those anticipated in the Anthropocene, stemming from changing climate, and growing water demand, energy exploitation and land use. For example, the warm, lower pH and oxygen depleted ocean that will come with global warming existed in the Phanerozoic and Proterozoic, during periods of profound global climatic and biologic instability. Warming, rapidly weathering soils in the coming century have analogs in Eocene paleosols (i.e., in the Bighorn Basin, WY) or in the post-glacial phase of Proterozoic glaciations (i.e., in the aftermath of the "Snowball Earths"). Such efforts should link studies of analogous past and present environments that represent conditions anticipated in the coming decades to century, while also providing resources to acquire and archive cores and support studies of modern environments.

We call for a bold initiative that links existing observatories, and develops new observatories that systematically characterize the past, present and evolving state of the near surface environment.

C. Basic Science and Observatories

Reaching comprehensive understanding of our planet needed to support future decision-making requires fundamental, basic scientific efforts, the hallmark of our field. Strong basic science will enhance our ability to exploit observatory results and to stimulate the next generation of observatory science. For example, we need innovative proxies for geobiological and geochemical states (in geochemical records, in organism's genetic data), new metrics for complexity and heterogeneity, advanced computational methods that bridge scales of observation and theory, and data integration and access. Observatories will be the engine to drive Critical Zone science forward, but they must be fueled by fundamental advances that emerge from basic research in geobiology and low-temperature geochemistry.

We call for strong support for observational and theoretical research in Geobiology and Low-Temperature Geochemistry that provide fundamental understanding of the surface environment and its inhabitants.

The Success of the Critical Zone Observatories

The Critical Zone Observatories (CZOs) are watersheds or groups of watersheds that are funded by NSF to enable investigations by geochemists, geobiologists, ecologists, soil scientists, hydrologists, geomorphologists, and geologists working together to study how the CZ functions and evolves. The CZOs promote these scientists to work as teams using field, laboratory, and modeling approaches to understand evolution of the Critical Zone. In a real sense, the CZOs are “spaceships” that are propelling workers to cross disciplinary divides between the environmental sciences.

The first three CZOs were funded with five-year grants from the Division of Earth Sciences (EAR) within the NSF Geosciences Directorate in 2007. Over the first several years of existence, the CZOs have been emplacing meteorological, hydrological, and geochemical instrumentation as well as collecting data and developing and testing models. In 2009, three more CZOs were funded to expand the CZO network.

Notable scientific outcomes from the CZOs so far include a model for how granitic weathering rates vary as a function of climate, the discovery of a worldwide but patchy signal of Mn contamination in soils in industrialized regions. *Perhaps the most important outcome to date, however, has been the fact that the community of scientists working on CZOs is now working across disciplines to develop models that couple chemistry, physics, and biology at a variety of spatial and temporal scales.* A manifestation of this effort is the CZO-led sharing of data online. In addition, CZO workers are collaborating with international scientists who are developing CZOs abroad. Indeed, the U.S.-led CZO effort has spawned four CZOs in Europe and similar efforts in China and Australia.

Importantly, NSF selected the six CZOs in the U.S.A. on their merit as individual sites and not based on how they function as a network. Sites vary in many attributes. For example, two of the original sites are located on granitic terrain (California, Colorado), and one on shale (Pennsylvania). NSF has promoted integrative modeling efforts across sites. For example, researchers at the CZOs in Arizona and Pennsylvania are leading an effort to quantify the rates and mechanisms of bedrock transformation using data from many sites worldwide as well as from the AZ, Colorado, and California CZOs. Some of the cross-site comparisons about the chemistry and biology of regolith and underlying bedrock are coordinated through the Critical Zone Exploration Network (CZEN). Projects spanning all three CZOs are also targeting dissolved organic carbon in surface waters, microbiological measurements within regolith, and the development of new instrumentation for hydrologic measurements. This latter effort has been coordinated with the Consortium of Universities for Advancement of Hydrologic Science (CUAHSI).

Although few in number, the CZOs have rapidly grown a community of scientists who are working together across disciplines and across scales of space and time. Notably, collaborators are using the facilities and are garnering funds from NSF to work at the CZOs. Such collaborations are generally initiated at each CZO by contacting the principal investigator. Many opportunities and gaps exist within the current CZOs and could provide the impetus for new field, laboratory, and modeling efforts. For example, the hydrological, geochemical, geomorphological, and ecological data that are now collected at CZOs often do not include new isotopic tracers being developed by the scientific community. Furthermore, many observations are needed to understand the biota and how it impacts rates of geochemical cycling of elements, evolution of regolith, and landscape evolution. These needs are especially important in the face of ongoing land use and climate change.

Figure 14 Location of existing Critical Zone Observatories; SS; Southern Sierra, BC, Boulder Creek, JR Jemez River, SH, Shale Hills, CR Christina River, LM, Luquillo

Above: Image representing earliest environments on the ancient Earth (Don Dixon, Space Art) and a modern map of anthropogenic light emission (image: NASA).

Front Cover: A retaining wall breach released waste sludge through the town of Devecser, Hungary from the Ajkai Timföldgyár plant in October, 2010. The sludge is a byproduct of refining bauxite into alumina (image: NASA).